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Vorenkamp

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(54) **VOLTAGE SUPPLY INTERFACE WITH CURRENT SENSITIVITY AND REDUCED SERIES RESISTANCE**

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(60) Provisional application No. 60/647,458, filed on Jan. 28, 2005.

(51) **Int. Cl.**
G05F 1/00 (2006.01)

(52) **U.S. Cl.** **323/272**; 323/283

(58) **Field of Classification Search** 323/283, 323/272, 282

See application file for complete search history.

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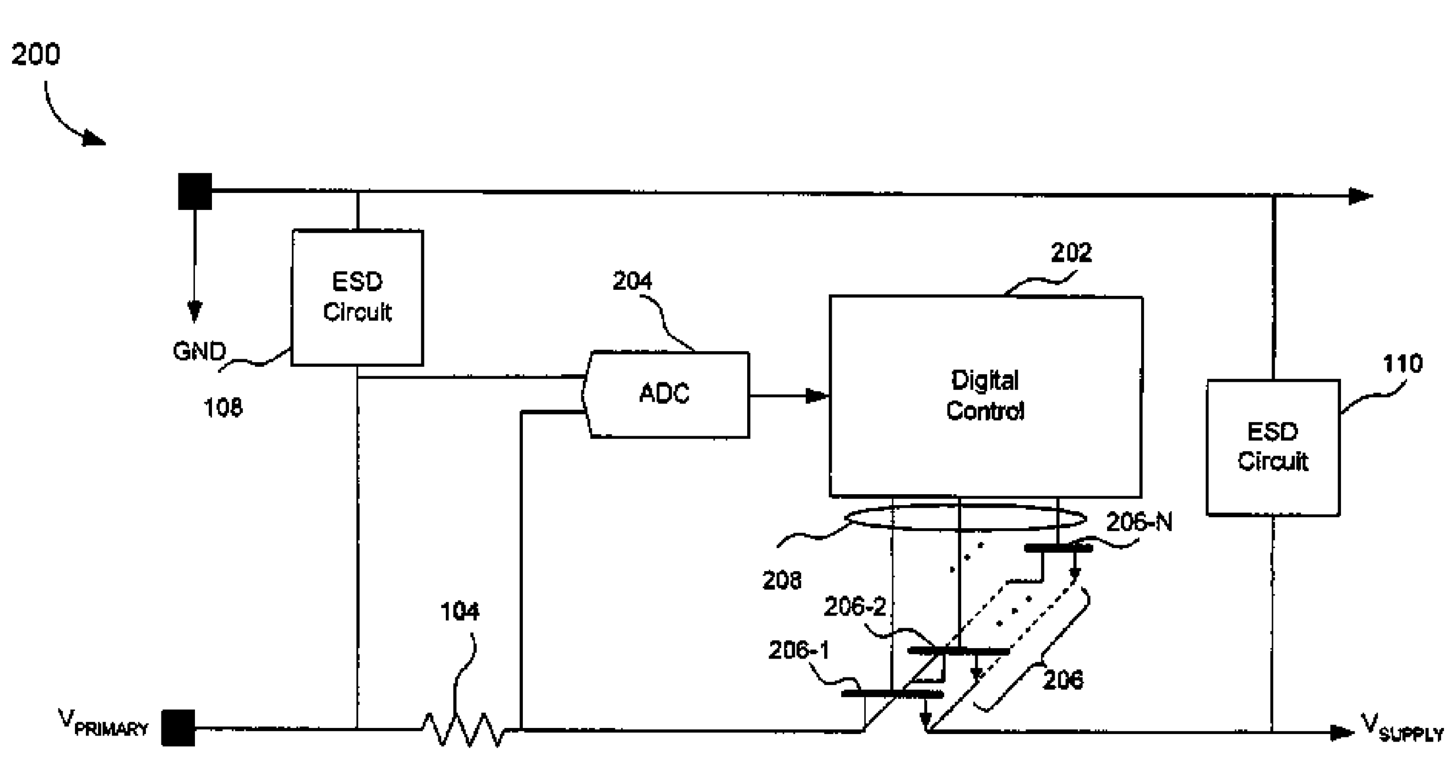
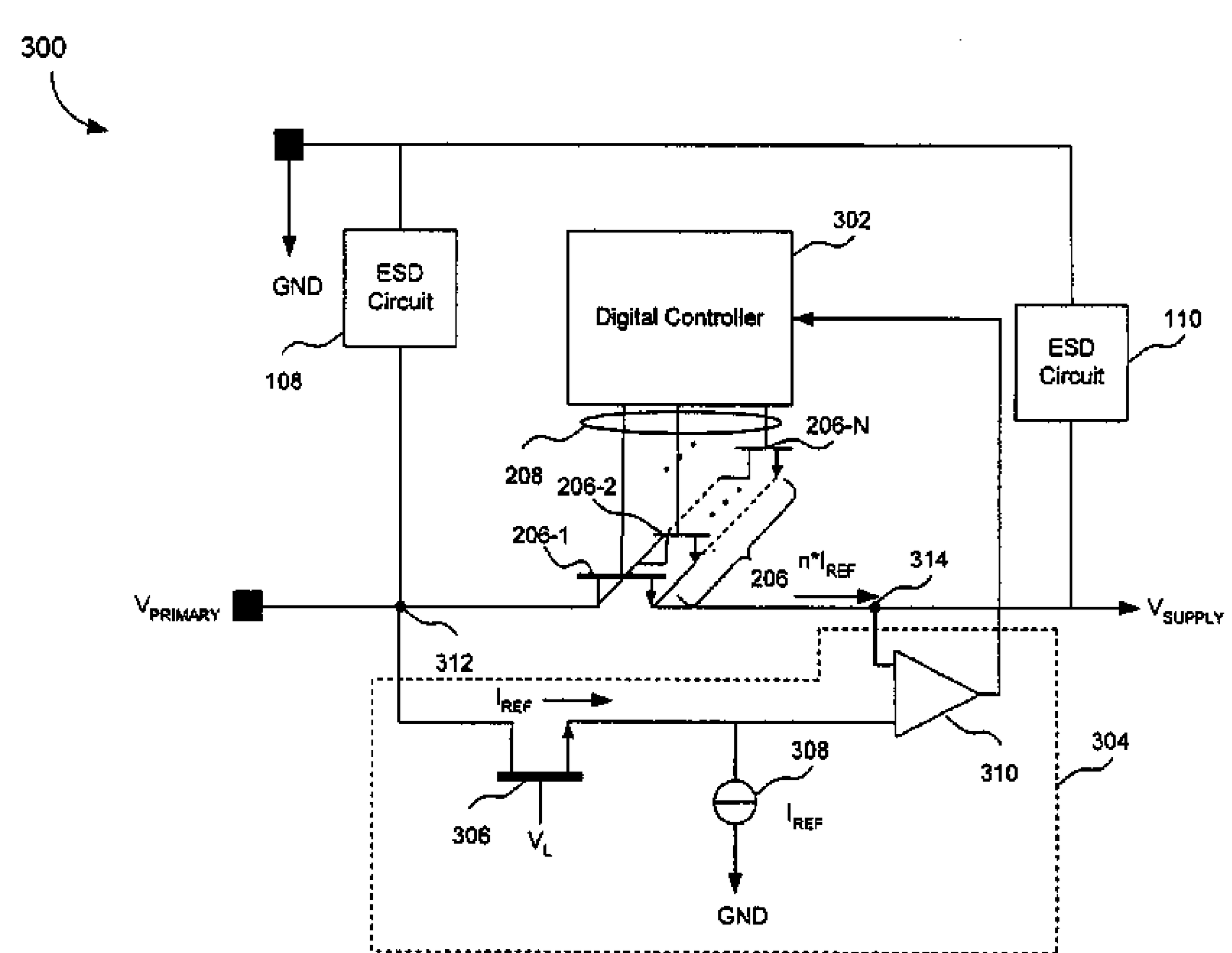
(57) **ABSTRACT**

A voltage supply interface provides both coarse and fine current control with reduced series resistance. The voltage supply interface has a segmented switch having N component switches that are digitally controlled. The voltage supply interface replaces a conventional sense resistor with a calibration circuit that has a replica switch that is a replica of the N component switches. The calibration circuit includes a reference current I_{REF} that is sourced through the replica switch. A voltage comparator forces a common voltage drop across the replica switch and the n-of-N activated component switches so that the cumulative current draw through the segmented switch is $n \cdot I_{REF}$. The current control of the voltage interface can be coarsely tuned by activating or deactivating component switches, and can be finely tuned by adjusting the reference current. The current sense resistor is eliminated so that the overall series resistance is lower.

17 Claims, 5 Drawing Sheets





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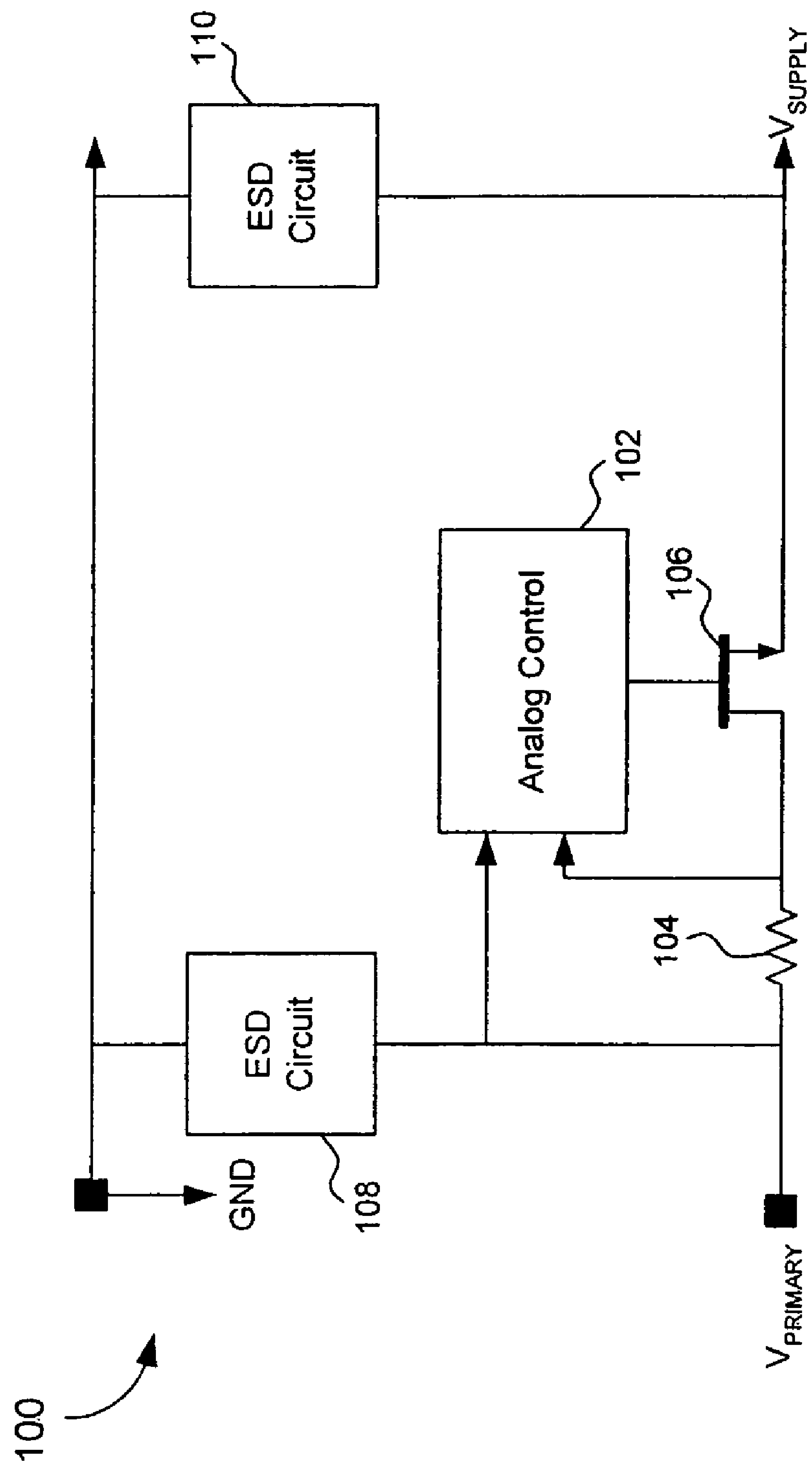

Conventional Art

FIG. 1

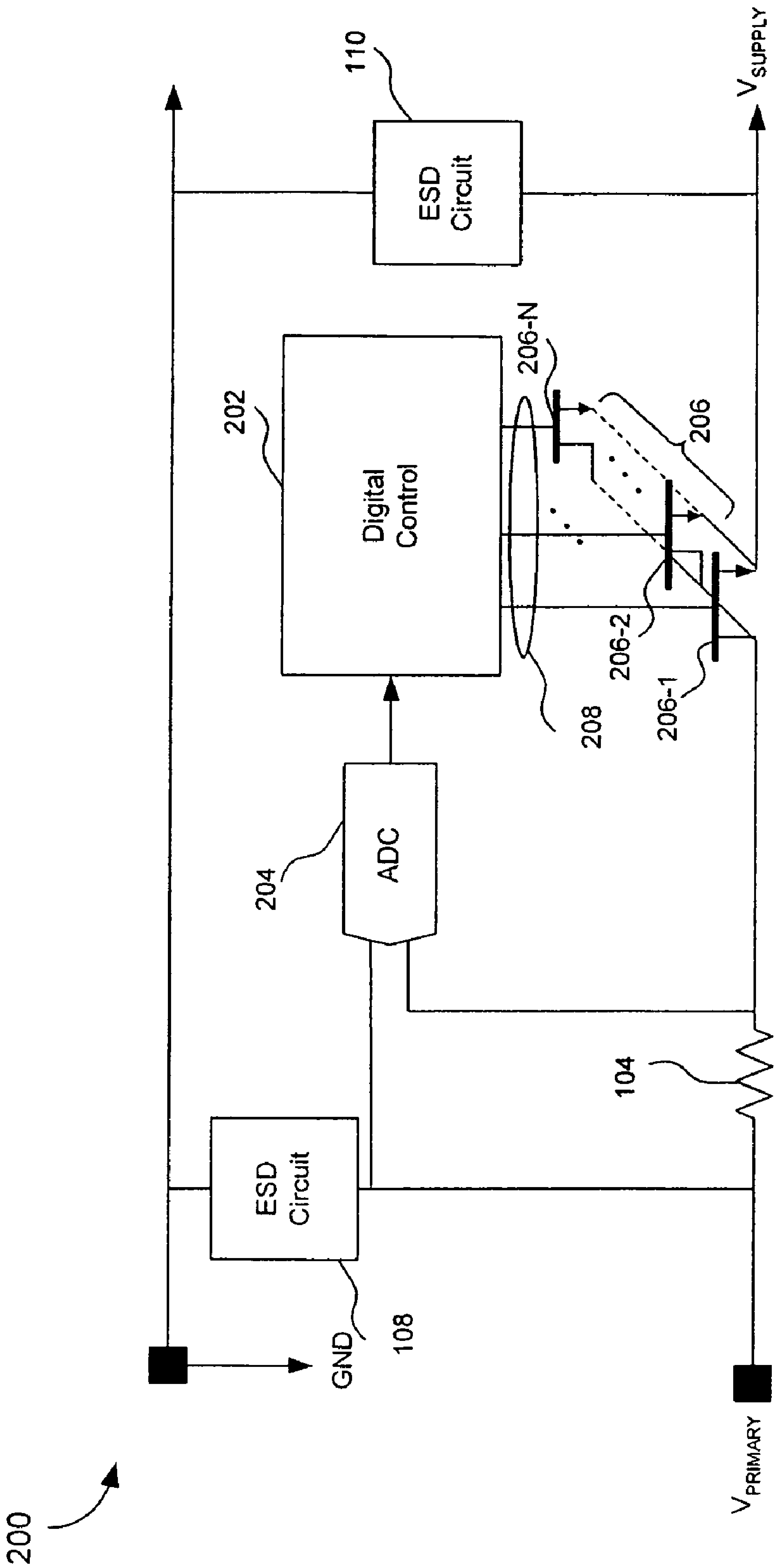
200
GND
108
ESD Circuit
104
$V_{PRIMARY}$
ADC
204
Digital Control
202
208
206-1
206-2
206
206-N
ESD Circuit
110
V_{SUPPLY}

FIG. 2

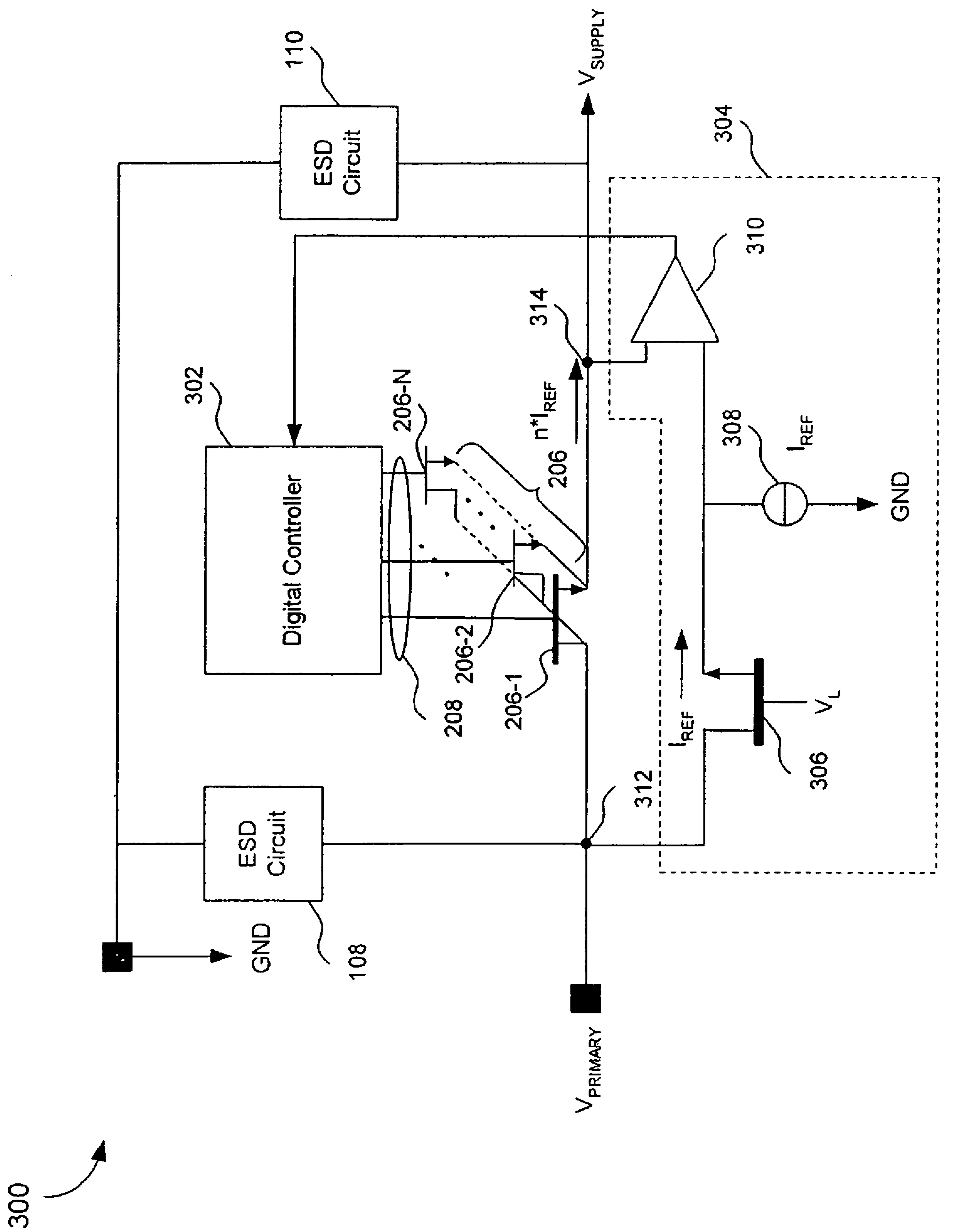
ESD Circuit
110
V_SUPPLY
304
310
314
302
Digital Controller
206-N
n*I_REF
206
308
I_REF
GND
206-2
206-1
208
V_L
I_REF
306
312
ESD Circuit
108
GND
V_PRIMARY
300

FIG. 3

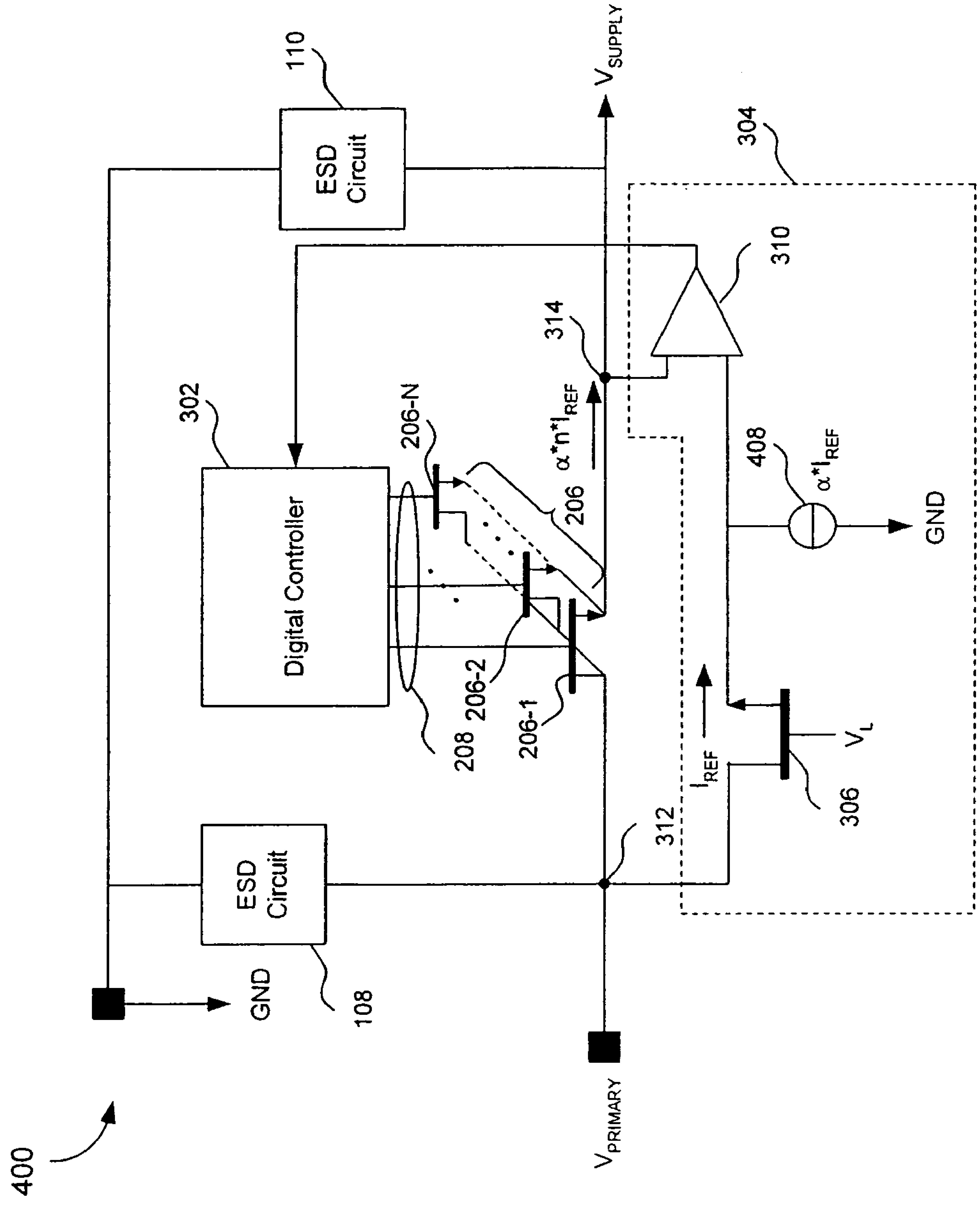
400
ESD Circuit
110
ESD Circuit
108
GND
V_{SUPPLY}
$V_{PRIMARY}$
Digital Controller
302
304
310
314
312
206-N
206
206-2
206-1
208
α*n*I_{REF}
408
α*I_{REF}
GND
I_{REF}
V_L
306

FIG. 4

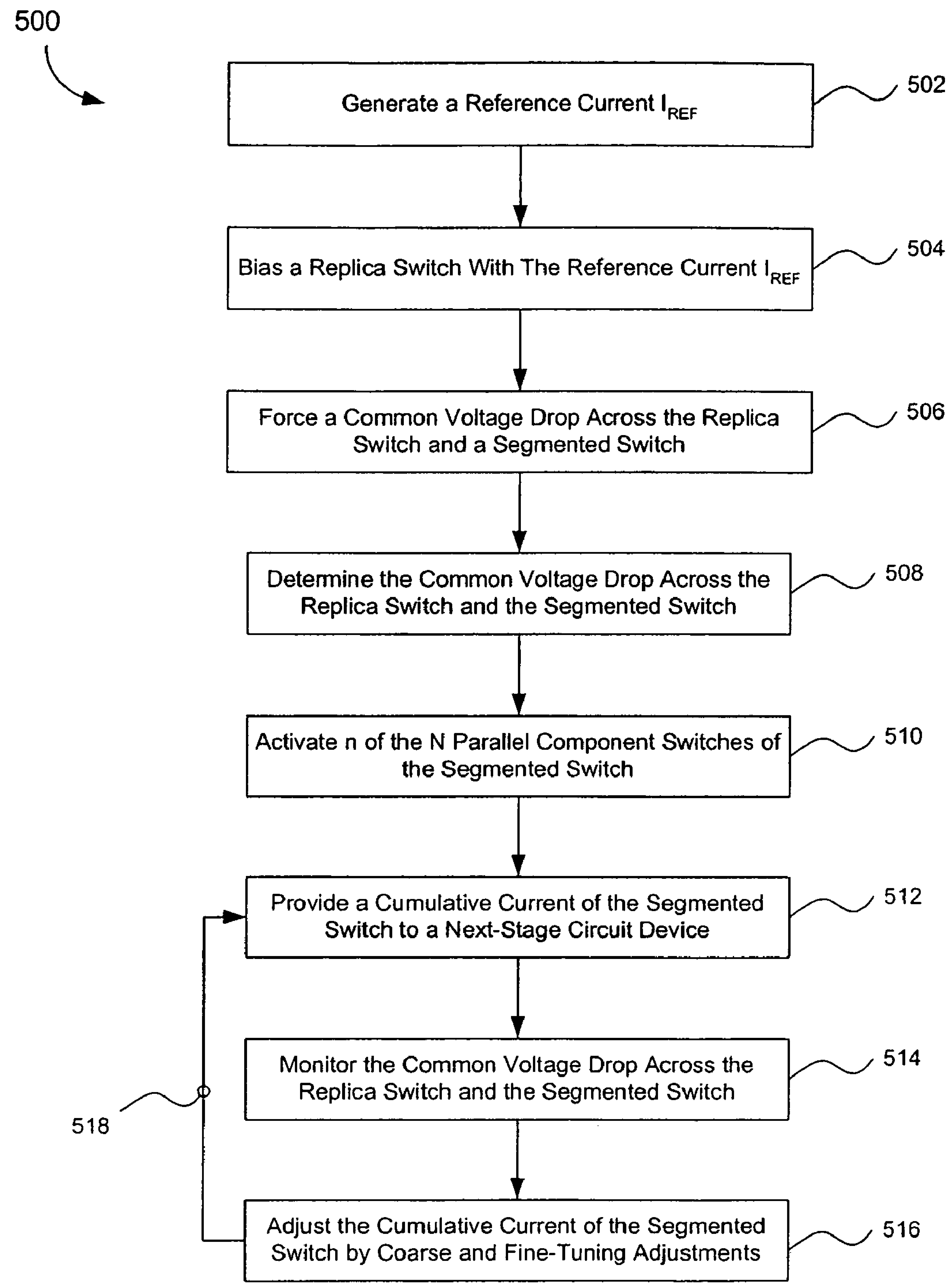
500
Generate a Reference Current I_REF
502
Bias a Replica Switch With The Reference Current I_REF
504
Force a Common Voltage Drop Across the Replica Switch and a Segmented Switch
506
Determine the Common Voltage Drop Across the Replica Switch and the Segmented Switch
508
Activate n of the N Parallel Component Switches of the Segmented Switch
510
Provide a Cumulative Current of the Segmented Switch to a Next-Stage Circuit Device
512
Monitor the Common Voltage Drop Across the Replica Switch and the Segmented Switch
514
Adjust the Cumulative Current of the Segmented Switch by Coarse and Fine-Tuning Adjustments
516
518

FIG. 5

VOLTAGE SUPPLY INTERFACE WITH CURRENT SENSITIVITY AND REDUCED SERIES RESISTANCE

CROSS REFERENCE TO RELATED APPLICATIONS

This application is a continuation of U.S. application Ser. No. 12/320,195, filed Jan. 21, 2009, which is a continuation of U.S. application Ser. No. 11/330,327, filed Jan. 12, 2006, now U.S. Pat. No. 7,498,779, which claims the benefit of U.S. Provisional Patent Application No. 60/647,458, filed Jan. 28, 2005, all of which are incorporated herein by reference in its entirety.

BACKGROUND OF THE INVENTION

1.Field of the Invention

The present invention generally relates to voltage supply interfaces. More specifically, the present invention provides a voltage supply interface having more accurate control and reduced series resistance.

2. Background Art

A voltage supply interface provides voltage and current to a next stage circuit device from a primary voltage supply. The voltage supply interface uses a switch to slowly power on the next stage circuit device when the next state circuit device is coupled to the primary voltage supply.

The voltage supply interface monitors the current supplied to the next stage circuit device to control the power supplied to the next stage circuit device. A conventional voltage supply interface uses a sense resistor that is in series with the next stage device to monitor the current. The sense resistor is required to be large to provide accurate current monitoring. A resulting large voltage drop across the sense resistor, however, reduces the power supplied to the next stage device. Further, supplying an adjustable current is difficult with the use of a single, inflexible switch.

Therefore, there exists a need for a voltage supply interface that provides more accurate control of the current supplied to the next stage device that minimizes or eliminates the power loss from the required sense resistor.

BRIEF SUMMARY OF THE INVENTION

A voltage supply interface provides both coarse and fine current control and reduced series resistance. The voltage supply interface has a segmented switch having N component switches that are digitally controlled. The voltage supply interface replaces a conventional sense resistor with a calibration circuit that has a replica switch that is a replica of the N component switches. The calibration circuit includes a reference current I_{REF} that is sourced through the replica switch. A voltage comparator forces a common voltage drop across the replica switch and the n-of-N activated component switches so that the cumulative current draw through the segmented switch is $n \cdot I_{REF}$. The current control of the voltage interface can be coarsely tuned by activating or deactivating component switches, and can be finely tuned by adjusting the reference current. The current sense resistor is eliminated so that the overall series resistance is lower.

In one embodiment of the invention, there is provided a voltage supply interface including a segmented switch, a calibration circuit and a digital controller. The segmented switch includes N parallel component switches. The calibration circuit is coupled in parallel with the segmented switch and provides a reference current I_{REF}. The digital controller is

coupled between the calibration circuit and the segmented switch and activates n of the N parallel component switches. A common voltage drop across the segmented switch and the replica switch causes a cumulative current substantially equal to $n \cdot I_{REF}$ to flow through the segmented switch. The digital controller activates and deactivates the parallel component switches based on the common voltage drop. The calibration circuit includes a current source and a replica switch biased by the current source. The current source is adjusted to provide a fine-tuning of the cumulative current. The calibration circuit further includes a voltage comparator configured to provide the common voltage drop across the segmented switch and the replica switch. An output of the voltage comparator is coupled to the digital controller. The N parallel component switches and the replica switch are substantially the same size.

In another embodiment of the invention, there is provided a method for regulating a current provided to a next stage circuit device from a primary voltage supply. A replica switch is biased with a reference current I_{REF}. A common voltage drop is forced across the replica switch and a segmented switch that includes N parallel component switches. n of the N parallel component switches are activated based on the common voltage drop, thereby causing a cumulative current flowing through the segmented switch to be substantially equal to $n \cdot I_{REF}$. A voltage comparator forces the common voltage drop and provides an indication of the common voltage drop to a digital controller. The digital controller activates and/or deactivates parallel component switches based on the common voltage drop to provide coarse control of the cumulative current. The reference current is adjusted to provide fine-tuning control of the cumulative current.

In another embodiment of the invention, there is provided voltage supply interface including a replica switch, a segmented switch, a voltage comparator and a digital controller. The replica switch is biased with a reference current I_{REF}. The segmented switch is coupled in parallel to the replica switch and includes a plurality of parallel component switches. The voltage comparator provides a common voltage drop across the segmented switch and the replica switch. The digital controller activates zero or more of the parallel component switches based on the common voltage drop. A cumulative current flow through the segmented switch is substantially equal to a sum of the individual currents flowing through the zero or more activated parallel component switches.

Additional features and advantages of the invention will be set forth in the description that follows, and in part will be apparent from the description, or may be learned by practice of the invention. The advantages of the invention will be realized and attained by the structure and particularly pointed out in the written description and claims hereof as well as the appended drawings.

It is to be understood that both the foregoing general description and the following detailed description are exemplary and explanatory and are intended to provide further explanation of the invention as claimed.

BRIEF DESCRIPTION OF THE DRAWINGS/FIGURES

The accompanying drawings illustrate the present invention and, together with the description, further serve to explain the principles of the invention and to enable one skilled in the pertinent art to make and use the invention.

FIG. **1** illustrates a conventional voltage supply interface.

FIG. **2** illustrates a digital voltage supply interface.

FIG. 3 illustrates a calibrated digital voltage supply interface having lowered series resistance and coarse current adjustment capability according to the present invention.

FIG. 4 illustrates a calibrated digital voltage supply interface having reduced series resistance and both fine and coarse current adjustment capability according to the present invention.

FIG. 5 provides a flowchart of a method for regulating current flow to a next stage circuit device according to the present invention

DETAILED DESCRIPTION OF THE INVENTION

FIG. 1 illustrates a conventional voltage supply interface **100**. The conventional voltage supply interface **100** is coupled to a primary voltage supply $V_{PRIMARY}$. The conventional voltage supply interface **100** provides a voltage V_{SUPPLY} to a next stage circuit device. The conventional voltage supply interface **100** uses an analog control **102**, a sense resistor **104** and a switch **106** to provide power to the next stage circuit device. The switch **106** is typically implemented with a Field Effect Transistor (FET), but this invention is not limited to such process technology only. Other process technologies could be used as will be recognized by those skilled in the arts.

The conventional voltage supply interface **100** often incorporates Electro-Static Discharge (ESD) protection. As shown in FIG. **1**, the conventional voltage supply interface **100** includes an ESD circuit **108** coupled between $V_{PRIMARY}$ and a ground potential (GND). The ESD circuit **108** protects the analog control **102** and the switch **106**. The conventional voltage supply interface **100** also includes an ESD circuit **110** coupled between V_{SUPPLY} and GND. The ESD circuit **110** protects the next stage circuit device coupled to V_{SUPPLY}.

The sense resistor **104** is coupled in series with the switch **106**. The analog control **102** monitors the voltage drop across the sense resistor **104**. The resistance of the sense resistor **104** is a known value and allows the analog control **102** to accurately measure the current flowing through the switch **106**. The analog control **102** adjusts the current supplied by V_{SUPPLY} by tuning the conductivity of the switch **106** based on the voltage measured across the sense resistor **104**.

The analog control **102** slowly turns on the switch **106** when a next stage circuit device is coupled to V_{SUPPLY}. By slowly turning on the switch **106**, the analog control **102** slowly turns on the next stage circuit device. As the next stage circuit device is powered up, and once the next stage circuit device is fully turned on, the analog control **102** and the switch **106** behave as an electronic fuse. That is, the analog control **102** monitors the current supplied to the next stage circuit device and cuts off the switch **106** if the current exceeds a maximum level.

Typically, the current flow through the sense resistor **104** is small. The resistance of the sense resistor **104** is therefore required to be large for the analog control **102** to accurately measure current. The total resistance between $V_{PRIMARY}$ and V_{SUPPLY} is determined by the sum of the resistance of the sense resistor **104** and the on-resistance of the switch **106**. This combined series resistance decreases the voltage supplied to the next stage circuit device by V_{SUPPLY}. Essentially, the voltage drop across the switch **106** and the sense resistor **104** translates into wasted power. Therefore, it is desired to keep the sum of the resistance of the sense resistor **104** and the on-resistance of the switch **106** as small as possible.

To keep the sum of the resistance of the sense resistor **104** and the on-resistance of the switch **106** small requires making the on-resistance of the switch as small as possible. The on-resistance of the switch **106** must be small because the resistance of the sense resistor **104** must be relatively large for accurate current monitoring purposes. The on-resistance of the switch **106** is reduced by making the FET size large. However, this increases die size, and will increase the parasitic capacitances of the switch **106**.

FIG. **2** illustrates a digital voltage supply interface **200**. The digital voltage supply interface **200** includes a digital control **202**, an analog-to-digital converter (ADC) **204**, the sense resistor **104** and a segmented switch **206**. The segmented switch **206** is comprised of N parallel switches (shown as switches **206-1**, **206-2** . . . **206**-N). Each of the N parallel switches can be implemented with FETs that are of the same size. In another embodiment, the FETs composing the N-parallel switches are sized differently from each other. For example, the size of the FETs comprising the N-parallel switches could be binary weighted relative to each other, or some other sizing scheme could be used. In other words, different size ratios of the N parallel switches are not to be excluded from this invention (e.g. binary weighted switch sizing)

The ADC **204** measures the voltage drop across the sense resistor **104** and provides a digital indication of the voltage drop to the digital control **202**. The digital control **202**, based on the measured voltage drop across the sense resistor **104**, turns on or turns off a portion of the N parallel FETs to adjust the current flow to V_{SUPPLY}. Specifically, the gates of the N parallel FETs are driven by an N-bit wide control word **208** issued by the digital control **202** to adjust the current flow.

The on-resistance of the segmented switch **206** is determined by the parallel combination of the on-resistances of the FETs turned on by the digital control **202**. More current flows through the segmented switch **206** as more of the component FETs are switched on. Less current flows through the segmented switch **206** as more of the component FETs are switched off. In this way, the parallel combination of the N FETs that make up the segmented switch **206** provides more accurate control and regulation of the current supplied to the next stage circuit device than provided by the switch **106** of the conventional voltage supply interface **100**.

FIG. **3** illustrates a calibrated digital voltage supply interface **300** of the present invention. The calibrated digital voltage supply interface **300** includes the segmented switch **206** composed of N parallel FETs. The segmented switch **206** is connected to a digital controller **302**. The calibrated digital voltage supply interface **300** also includes a calibration circuit **304**. The calibration circuit **304** includes a replica switch **306**. The replica switch **306** is implemented with a FET that is of the same size as each of the N parallel FETs that comprise the segmented switch **206**. The replica switch is biased with a low bias voltage V_L (and therefore the replica switch is turned "ON") The replica switch **306** is connected to $V_{PRIMARY}$ and the segmented switch **206** at a node **312**.

As further shown in FIG. **3**, the calibration circuit **304** includes a current source **308**. The current source **308** provides a reference current I_{REF}. The calibration circuit **304** also includes a voltage comparator **310** that could be implemented as a differential amplifier. A first input of the **310** is coupled to both the current source **308** and the replica switch **306**. A second input of the voltage comparator **310** is connected to a node **314**. An output of the voltage comparator is connected to the digital controller **302**.

During operation, the current flowing through the replica switch **306** is equal to I_{REF}. The voltage comparator **310** forces the voltage drop across the replica switch **306** to be equal to the voltage drop across the segmented switch **206**. At any one time, n of the N parallel FETs within the segmented switch **206** are turned on. Therefore, the voltage drop across the one FET that makes up the replica switch **306** is equal to the voltage drop across the n parallel FETs that are turned on within the segmented switch **206**. This causes a cumulative current equal to $n \cdot I_{REF}$ to flow through the segmented switch **206** when the n parallel FETs are equal in size to each other, and to the replica switch **306**. Alternatively, different cumulative current values for the segmented switch **206** can be created by sizing the parallel component switches to be different from each other, as was discussed above. For example, the parallel component switches can be sized so as to have a binary weighting relative to each other, so to produce corresponding binary weighted current increments. As such, each segmented switch can be broadly described as producing a corresponding individual current that is proportional to I_{REF} (including fractions and multiples of I_{REF}), so that changes in I_{REF} produce corresponding changes in individual parallel component currents of the segmented switch **206**. In turn, a large current is supplied to the next stage circuit device coupled to the calibrated digital voltage supply interface **300**.

The current that flows through the segmented switch **206** can be coarsely controlled by the digital controller **302**. That is, the digital controller **302** can successively turn on or turn off the component FETs within the segment switch **206** in order to increase or decrease the current provided to the next stage circuit device. The current flow provided to the next stage device can vary between no current and a current equal to $N \cdot I_{REF}$. This range is subdivided or quantized into N equal increments of a current equal to I_{REF}.

FIG. **4** illustrates a calibrated digital voltage supply interface **400** having both fine and coarse tuning capability according to the present invention. The calibrated digital voltage supply interface **400** includes an adjustable current source **408**. For example, the adjustable current source **408** can be a programmable current source. The adjustable current source **408** can adjust the current supplied to the replica switch **306** and therefore the segmented switch **206**. Specifically, the current I_{REF} provided by the adjustable current source **408** can be adjusted by a factor α.

Adjusting the current I_{REF} by the factor a provides a fine-tuning adjustment of the current that is supplied to the next stage circuit device. Therefore, the calibrated digital voltage supply interface **400** provides coarse current adjustment by switching on component FETs within the segmented switch **206** and also provides fine current adjustment by adjusting the size of the reference current I_{REF} supplied by the adjustable current source **408**. Overall, a cumulative current equal to $\alpha \cdot n \cdot I_{REF}$ flows through the segmented switch **206**.

Both the calibrated digital voltage supply interface **300** depicted in FIG. **3** and the calibrated digital voltage supply interface **400** depicted in FIG. **4** provide an overall lower series resistance. Specifically, the need for a large sense resistor for monitoring current flow has been eliminated. With the large sense resistor eliminated, the calibrated digital voltage supply interface **300** and calibrated digital voltage supply interface **400** can tolerate higher on-resistances from the component FETs within the segmented switch **206**. In turn, these component FETs can be made smaller which reduces space requirements and parasitic capacitances. The accuracy of a conventional voltage supply interface is limited by the large sense resistor. With the calibrated digital voltage supply interface **300** and calibrated digital voltage supply interface **400**, this limitation is removed and accuracy is now determined by the matching of the component FETs within the segment switch **206** and the FET within the replica switch **306**.

FIG. **5** provides a flowchart **500** that illustrates operational steps corresponding to FIG. **4**, for regulating current flow to a next stage circuit device by a voltage supply interface, according to the present invention. The invention is not limited to this operational description. Rather, it will be apparent to persons skilled in the relevant art(s) from the teachings herein that other operational control flows are within the scope and spirit of the present invention: In the following discussion, the steps in FIG. **5** are described.

At step **502**, a reference current equal to I_{REF} is generated by an adjustable current source.

At step **504**, a replica switch is biased by the reference current I_{REF}.

At step **506**, a voltage drop across a segmented switch is forced to be equal to a voltage drop across the replica switch.

At step **508**, the common voltage drop across the replica switch and the segmented switch is determined.

At step **510**, n of the N parallel component switches comprising the segmented switch are activated.

At step **512**, a cumulative current equal to $n \cdot I_{REF}$ is provided to the next stage circuit device.

At step **514**, the common voltage drop across the replica switch and the segmented switch is monitored.

At step **516**, the cumulative current provided to the next stage device is adjusted. Coarse adjustments are made by either turning on or turning off parallel component switches of the component switch. Turning on additional parallel component switches coarsely increases the cumulative current flow through the segmented switch. Turning off additional parallel component switches coarsely decreases the cumulative current flow through the segmented switch. Fine-tuning adjustments are made by adjusting the reference I_{REF} current provided by the adjustable current source. Specifically, the reference current I_{REF} is adjusted by a factor a such that the cumulative current flow through the segmented switch is equal to $\alpha \cdot n \cdot I_{REF}$.

A voltage supply interface operating according to the flowchart **500** will provide this adjusted cumulative current to the next stage device, and will continue to monitor and adjust the cumulative current flow, as indicated by the repeat operation step **518**.

CONCLUSION

While various embodiments of the present invention have been described above, it should be understood that they have been presented by way of example and not limitation. It will be apparent to one skilled in the pertinent art that various changes in form and detail can be made therein without departing from the spirit and scope of the invention. Therefore, the present invention should only be defined in accordance with the following claims and their equivalents.

What is claimed is:

1. A voltage supply interface, comprising:

a segmented switch comprising N component switches, the segmented switch configured to receive a voltage supply input and to provide a current output determined by the number of components switches of the N component switches that are activated; and

a replica switch that is similar to at least one of the component switches, and that is configured to be biased by a reference current;

wherein the segmented switch and the replica switch are configured to have a common voltage drop so that each activated component switch of the segmented switch conducts a current proportional to the reference current and contributes to the current output.

2. The voltage supply interface of claim 1, wherein coarse tuning of said current output is performed by incrementally activating or de-activating component switches of said segmented switch.

3. The voltage supply interface of claim 1, wherein fine tuning of the current output is performed by adjusting the reference current that is used to bias the replica switch.

4. The voltage supply interface of claim 3, wherein said reference current is supplied by an adjustable current source.

5. The voltage supply interface of claim 1, further comprising:

a controller configured to determine the number of activated component switches of the N component switches in order to coarsely tune the current output.

6. The voltage supply interface of claim 5, wherein the number of activated component switches of the N component switches is based on a current requirement of a next stage circuit that receives said current output of the voltage supply interface.

7. The voltage supply interface of claim 5, further comprising:

an adjustable current source configured to provide the reference current, wherein said current output is finely tuned by adjusting said adjustable current source.

8. The voltage supply interface of claim 7, wherein the adjustable current source is determined based on a current requirement of a next stage circuit that receives said current output from said voltage supply interface.

9. The voltage supply interface of claim 1, wherein coarse tuning of said current output is performed by incrementally activating or de-activating component switches of the N component switches of the segmented switch; and wherein fine tuning of the current output is performed by adjusting the reference current that is used to bias the replica switch.

10. The voltage supply interface of claim 9, wherein the coarse tuning and the fine tuning are determined based on a current requirement of a next stage circuit that receives said current output from said voltage supply interface.

11. The voltage supply interface of claim 1, wherein the components switches are arranged in parallel with each other.

12. The voltage supply interface of claim 11, wherein the replica switch is arranged in parallel with at least one component switches.

13. The voltage supply interface of claim 1, wherein a component switch is activated by closing the component switch so that its current contributes to the current output, and wherein a component switch is deactivated by opening the component switch.

14. The voltage supply interface of claim 1, wherein replica switch is the same size of at least one of the component switches.

15. The voltage supply interface of claim 1, further comprises a voltage comparator, wherein:

a first input of the voltage comparator is coupled to the current source and the replica switch;

a second input of the voltage comparator is coupled to an output of the segmented switch; and

an output of the voltage comparator is coupled to a digital controller that controls the segmented switch.

16. The voltage supply interface of claim 15, wherein:

the voltage comparator is configured to force the common voltage drop between the segmented switch and the replica switch; and

the voltage comparator is configured to provide an indication of the common voltage drop to the digital controller; and

the digital controller is configured to close the n of the N parallel component switches based on the indication of the common voltage drop.

17. The voltage supply interface of claim 1, wherein the component switches of the segmented switch are sized differently from each other.

* * * * *